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DOCUMENT-IDENTIFIER: US 5243541 A
TITLE: Imaging lidar system for shallow and coastal water

ABPL:
An imaging lidar system for underwater applications is Presented which is well
suited for imaging and detecting underwater targets suspended above and on the
bottom in shallow and coastal water. The present invention provides the
capability for rapid and reliable search, detection, classification and
localization of objects in the surf zone which may present hazards to navigation
and utilization of coastal areas as well as undesirable effluents and biological
fouling of underwater objects. The present invention employs an improved bottom
tracker for accurately measuring the distance between the imaging lidar system
and the bottom.

BSPR:
This invention relates generally to a sensor system for remote detection and
imaging of objects in a backscattering medium such as water. More particularly,
this invention relates to a method and apparatus for detecting, locating and/or
imaging underwater objects in shallow water and in coastal regions from an
airborne platform using a novel imaging lidar (light detection and ranging)
system which improves imaging in such shallow water areas.

BSPR:
Presently, cumbersome and time consuming wire line devices must be used for
detecting underwater targets from remote airborne locations. These devices are
lowered into the water and are easily subject to damage and loss. Also, wire line
devices make target searching relatively slow and can only detect targets without
providing visual imaging.

BSPR:
An improved and novel system for remote detection and imaging of objects
underwater (or objects obscured by other backscattering media which are at least
partially transmitting to light such as ice, snow, fog, dust and smoke) from an
airborne platform has been described in U.S. Pat. No. 4,862,257 and U.S. Pat. No.
5,013,917, both of which are assigned to the assignee hereof and incorporated
herein by reference. The imaging lidar system of U.S. Pat. No. 4,862,257 utilizes
a laser to generate short pulses of light with pulse widths on the order of
nanoseconds. The laser light is expanded by optics and projected down toward the
surface of the water and to an object or target. U.S. Pat. No. 5,013,917 relates
to an imaging lidar system intended for night vision.

BSPR:
Imaging lidar systems of the type described hereinabove are also disclosed in
commonly assigned U.S. Pat. No. 4,964,721 and U.S. Pat. No. 4,967,270, both of
which are incorporated herein by reference. U.S. Pat. No. 4,964,721 relates to an
imaging lidar system which controls camera gating based on input from the
aircraft onboard altimeter and uses a computer to thereby adjust total time delay
so as to automatically track changing platform altitude. U.S. Pat. No. 4,967,270
relates to a lidar system employing a plurality of gated cameras which are
individually triggered after preselected time delays to obtain multiple subimages
laterally across a target image. These multiple subimages are then put together
in a mosaic in a computer to provide a complete image of a target plane
preferably using only a single light pulse.

BSPR:

Still other imaging lidar systems are disclosed in commonly assigned U.S. Pat. Nos. 5,029,009 and 5,034,810, both of which are incorporated herein by reference. U.S. Pat. No. 5,029,009 describes an imaging lidar system incorporating an imaging camera having a plurality of gating electrodes on a focal plane and means for producing variable time delay gating across an image viewed by the focal plane. U.S. Pat. No. 5,034,810 relates to a two wavelength lidar imaging system for underwater application utilizing image subtraction to detect passage of internal waves or other anomalies under water.

BSPR:
U.S. Ser. No. 565,631 filed Aug. 10, 1990 which is also assigned to the assignee hereof and fully incorporated herein by reference, relates to an airborne imaging lidar system which employs a plurality of pulsed laser transmitters, a plurality of gated and intensified array camera receivers, an optical scanner for increased field of regard, and a computer for system control, automatic target detection and display generation. U.S. Ser. No. 565,631 provides a means for rapidly searching a large volume of the backscattering medium (e.g., water) for specified targets and improves upon prior art devices in performance as a result of having more energy in each laser pulse (due to simultaneous operation of multiple lasers) and a more sensitive detection system using multiple cameras. The several cameras may be utilized to image different range gates on a single laser pulse or several cameras can be gated on at the same time to provide independent pictures which can then be averaged to reduce the noise level and improve sensitivity. Both of these improvements result in higher signal-to-noise ratio and thus higher probability of detection or greater range of depth capability.

BSPR:
Imaging lidar systems of the type hereinabove discussed are often used in conjunction with computerized automatic target detection (ATD) systems for detecting, locating and identifying targets from a plurality of two dimensional images. Examples of such ATD systems are described in commonly assigned U.S. application Ser. Nos. 565,425 and 565,424, both of which were filed on Aug. 10, 1990 and are incorporated herein by reference.

BSPR:
While the imaging lidar systems described above are well suited for their intended purposes (particularly deep ocean detection), there continues to be a need for imaging lidar systems of this type which have improved operational performance and efficiency in the imaging of underwater targets found in shallow water and/or coastal regions. Such coastal zone surveillance presents an even more challenging problem than deep ocean detection. These difficult problems are encountered as a result of the more challenging conditions in shallow water than those encountered previously in deeper water. These factors include highly variable conditions at the air/water interface such as breaking waves, foam and spray, spatially varying bottom depths both parallel and perpendicular to the coastline and the need for high spatial resolution in order to detect and classify small objects which may be partly hidden in the sand.

BSPR:
Notwithstanding the foregoing, the need for imaging lidar systems, suitable for such coastal and shallow water applications is of great interest to government and commercial activities. For example, there continues to be an increasing need for identification of natural and man made obstacles and hazards in the coastal regions. Obvious applications include identifying favorable sites for construction and utilization of shallow water ports and moorings, surveillance of coastal areas to monitor changes in the surf zone as a result of sediment loading or storm activity, and localization and identification of underwater debris as part of search and rescue operations. Other applications involve the detection of obstacles, mines and hidden explosive charges in shallow waters, offshore and in certain riverine environments. Natural and man made underwater effluent and biological fouling of underwater intake and discharge lines such as that caused by the Zebra mussel in the Great Lakes also needs to be identified.

BSPR:
An imaging lidar apparatus specifically configured to meet the problems associated with imaging objects in shallow water and surf zones is disclosed in U.S. application Ser. No. 774,665 filed Oct. 11, 1991 (which is assigned to the assignee hereof and incorporated herein by reference). This apparatus comprises an airborne imaging lidar system for detection and classification of objects in

the surf zone of coastal waters. Preferably, the lidar transmitter is a
repetitively pulsed Nd:YAG laser illuminating a portion of the coastal marine
area for imaging by a gated camera (e.g., CCD camera) with optimized gating time
delay. This prior apparatus also utilizes high spatial resolution and target
detection algorithms to classify objects and discriminate against clutter. As a
result, this device is capable of rapid search of coastal areas, performs real
time automatic target detection, noise rejection and classification, and is
capable of both day and night operations under a wide range of sea state and
water clarity.

BSPR:
Important features of the apparatus of U.S. Ser. No. 774,663 include multiple
imaging cameras to provide high spatial resolution, a bottom tracker to maintain
camera gating at the optimum local bottom depth, a specialized beam projection
system to minimize brightness variations across the field of view and which
optimizes the spatial relationship of the transmitted light to the geometry of
the receiver optics, and finally, target detection computers to provide real time
detection and classification of surf zone obstacles.

BSPR:
Notwithstanding these important features and advantages, there continues to be a
need for imaging lidar systems of the type described in U.S. Ser. No. 774,663
having even more improved spatial resolution and target locating abilities than
is currently available from prior art systems. This need is particularly apparent
in the field of mine detection. It is desirable to fly the sensor platform
parallel to the water line and somewhat offshore. It is also desirable to search
the beach, surf zone, and shallow water zone in a single pass. This is not
practical to do with the staring sensor of U.S. Ser. No. 774,663 because of the
very large number of pixels required to effectively detect mines as small as six
inches in diameter.

BSPR:
The range gate isotemporal contours are spheres, and this means that large
instantaneous field of view (IFOV) cameras associated with the system of U.S.
Ser. No. 774,663 are not desirable since, in this case, part of the image may be
the air above the water, part may be water surface glints, part may be water
volume backscatter, part may be ocean bottom reflections, and Part may even be
"below" the bottom, thus containing only residual sunlight which leaks through
the narrow bandpass filter in the camera which is matched to the laser
wavelength. Thus, for two reasons, pixel density and range gate curvature, the
camera IFOV must be small.

BSPR:
The above-discussed and other problems and deficiencies of the prior art are
overcome or alleviated by the imaging lidar system of the present invention. In
accordance with the present invention, an imaging lidar system of the type
described in U.S. Ser. No. 774,663 (a pulsed laser transmitter and one or more
range-gated camera receivers) employs a novel bottom detector for providing
accurate water depth information. More specifically, the bottom detector
comprises a separate, dedicated photodetector which, along with a computer is
used to determine the appropriate time delay for operating the range-gated
camera(s). During operation, for each laser pulse that the laser transmitter
delivers to the target area, the single photodetector of the present invention is
used to determine the desired time delay which is then loaded digitally into a
programmable delay generator for delaying the camera gate after the next laser
pulse.

BSPR:
The present invention thus provides accurate water depth information for the
purpose of adjusting receiver delay generators used in airborne imaging LIDAR
detection systems. The present invention is particularly well suited for
applications where the water depth must be accurately known in order to obtain
optimized images for the purpose of detecting targets resting on the ocean bottom
in the surf zone or on the beach above the water line. In such applications, the
variations in water depth both parallel and perpendicular to the water line must
be determined in real time in order to effectively search large areas for mine
fields. Additional information such as air visibility, wave height, bottom
roughness, bottom reflectance, and water clarity can also be determined using the
optical sensor of the present invention.

DRPR:
FIG. 1 is a block diagram of an imaging lidar system in accordance with the present invention;

DEPR:
Detection, classification and localization of objects in the surf zone presents a formidable challenge to remote sensors. The instrument must have high spatial resolution to a adequately classify obstacles and discriminate against clutter, the sensor must be adaptable to rapidly varying bottom depths and sea surface elevations, and must contend with large variability in sea surface conditions (e.g., breaking waves and foam), and be robust with respect to variable conditions in ambient light and water clarity. These requirements are met in the present invention as shown in the block diagram of FIG. 1 by using active illumination (e.g., laser) to overcome variations in natural illumination, a gateable camera for discrimination against ambient noise, automatic gate timing to follow variations in bottom depth, an imaging array to provide high spatial resolution and a high speed computer for automatic target detection, classification and display. A particularly important features of this invention includes the incorporation of a novel bottom detector for providing the desired time delay to a programmable delay generator for delaying the camera gating after each laser pulse. This novel bottom detector is shown in the block diagram of FIG. 2.

DEPR:
Referring first to FIG. 1, a master clock 10 periodically outputs a pulse which fires the pulsed laser 12, strobes (e.g., triggers) the operation of the bottom detector 14, and triggers the digital delay generator 16 which, after the time delay provided by bottom detector 14 from the previous pulse at this scan angle, gates the electronic shutter of the imaging camera 18, which is typically an intensified CCD.

DEPR:
FIG. 2 shows the major elements of bottom detector 14. Light backscattered from below the aircraft first passes through a narrow spectral bandpass filter 20 to remove unwanted sunlight. Next, a lens 22 focuses the light upon a high speed photodetector 24 such as an avalance photodiode or a photomultiplier tube. The electrical current produced by the photodetector is amplified and converted to a voltage signal in a transimpedance preamplifier 26. Next, an output voltage proportional to the logarithm of the input signal is produced by a logarithmic converter/amplifier 28. This signal is then repetitively converted to a digital value in a high speed analog-to-digital converter 30. A fixed number of digital values are measured for each laser pulse starting immediately after the laser is fired. This data is processed in a built-in (or external) digital computer 32 (using scanner angle and aircraft pitch, roll, and altitude information) to determine the desired information including water depth. The bottom detector optical axis is matched to that of the imaging camera 18 and the bottom detector optical axis will have a smaller FOV, so the depth measurement from bottom detector 18 corresponds to an average depth over the central portion of the camera image.

DEPR:
Turning to FIG. 3, the bottom tracker disclosed is U.S. Ser. No. 774,663 (corresponding to FIG. 5 of U.S. Ser. No 774,663) is shown at 66. As described in U.S. Ser. No. 774,663, bottom tracker 66 includes input optics 100, a narrow bandpass optical filter 102 matched to the laser wavelength, a photomultiplier tube or avalance photodiode 104 and a preamplifier/discriminator 106 for detecting the bottom reflection.

DEPR:
The remainder of the lidar system of this invention is identical to the imaging lidar system of U.S. Ser. No. 774,663 including a scanning mirror which can scan the transmitted beam and receiver fields of view along a common axis.

DEPR:
1. Laser pulse width--The full width at half maximum of the intensity of the laser pulse is denoted by .tau..sub.L.

DEPR:

2. Signal sampling period--The period for digitizing the photodetector signal is denoted by $.tau..sub.ADC$ which is selected to be about one-half the laser pulse width $.tau..sub.L$. The analog-to-ditigal integration width (sampling aperture) is denoted by $.delta..sub.ADC$ which will be $.1toreq..tau..sub.ADC$.

DEPR:
4. LIDAR System Constant--The bottom detector 14 output signal I has a value called the LIDAR System Constant $I.sub.o$ which is the signal detected when a 100% reflecting Lambertian surface is placed at zero range.

DEPR:
5. Air backscatter coefficient--The air between the sensor and the water will backscatter laser light with a coefficient given by $.beta..sub.air$ which has units of $m.sup.-1$ $sr.sup.-1$, For ease of understanding, it will be assumed that the LIDAR system is monostatic and the backscattering angle is $180.degree..$

DEPR:
7. Aircraft slant altitude--If the aircraft altitude is A feet, then the slant path length to the water surface is equal to $A.sub.s =A/cos(.theta.)$ where $.theta.$ is the angle from nadir of the sensor line of sight. The nadir viewing angle $.theta.$ will vary repetitively with time due to the sensor scanner motion. It will be appreciated that $cos (.theta.)=cos$ (pitch angle) cos (roll angle).

DEPR:
9. Water surface roughness--The temporal width of the return light pulse incident on the bottom detector from the water surface reflection is given by $.tau..sub.SR$ when the outgoing laser pulse has infinitely narrow temporal width (i.e., it is a Dirac delta function). This width will be determined by the RMS wave height value and by the range variation of the mean water surface over the bottom detector field of view. Thus, the width $.tau..sub.SR$ will be affected by the slant altitude and by the nadir viewing angle $.theta..$ If the bottom detector has a "rectangular" angular field of view which has half angles of $.theta..sub..vertline..vertline.$ and $.theta..sub..perp.$ in the directions parallel and perpendicular to the scanning plane (which is generally in the roll plane of the aircraft), then the minimum slant range is

DEPR:
As shown in FIG. 4, the apparent width of the water surface glint feature $W.sub.S$ is the convolution of the laser pulse width $.tau..sub.L$, the water surface roughness width $.tau..sub.SR$, the detector impulse response width $.tau..sub.D$, and the analog-to-digital integration width $.delta..sub.ADC$. It will be appreciated that a RMS wave height estimate will be meaningful only if the field of view of the bottom detector is small in the direction parallel to the scan (i.e., $.theta..sub..vertline..vertline.$ is small) and if the sensor viewing angle from nadir $.theta.$ is also small. The half angle of the IFOV in the direction perpendicular to the scan can be larger, leading to a rectangular IFOV with a large aspect ratio ($.theta..sub..perp. >>.theta..sub..vertline..vertline.$).

DEPR:
10. Water backscatter coefficient--The water volume will backscatter laser light with a coefficient given by $.beta..sub.water$ which has units of $m.sup.-1$ $sr.sup.-1$. For ease of understanding, it will again be assumed that the LIDAR system is monostatic and the backscattering angle is $180.degree..$

DEPR:
14. Bottom roughness--The temporal width of the light pulse incident on bottom detector 14 from the ocean bottom reflection 14 is given by $.tau..sub.BR$ when the outgoing laser pulse has infinitely narrow temporal width (i.e., it is a Dirac delta function). This width will be determined by the RMS bottom height variations and by the range variation of the mean bottom surface over the bottom detector field of view. Thus, the width $.tau..sub.BR$ will be affected by the slant altitude and by the nadir viewing angle $.theta..$ The minimum slant range in the water is

DEPR:
As shown in FIG. 4, the apparent width of the ocean bottom reflection feature $W.sub.B$ is the convolution of the laser pulse width $.tau..sub.L$, the bottom roughness width $.tau..sub.BR$, the detector impulse response width $.tau..sub.D$, and the analog-to-ditigal integration width $.delta..sub.ADC$. In order to

accurately determine the best depth estimate, it is important to limit the IFOV of bottom detector 14 in the direction parallel to the scan (i.e., keep .theta..sub..vertline..vertline. small) so that the ocean bottom reflection pulse is fairly narrow.

DEPR:
After a sufficient number of analog-to-digital conversions have been completed, computer 30 will perform a least squares fit of the variables in the time delay equation to optimally estimate their values. Then the time delay corresponding to the opening of the camera shutter is computed so that the camera range gate is approximately centered on the ocean bottom (the camera shutter should be opened at the time equal to .tau..sub.B minus half the camera gate width). Thus, half the gate is above the bottom and half is below the bottom. This gate timing maximizes the likelihood that the reflection from the bottom will fill the entire camera image and thus that mine-like objects resting on the bottom will be imaged. In all calculations, the assumption is made that, for any given scanner position, the ocean depth will not change appreciably (i.e., by more than one-half the gate width) over the distance parallel to the water line that the platform travels during the time between scanner looks at the same angle. This condition is generally met in areas otherwise suitable for amphibious assault.

DEPR:
Preferably, matrix calculations are used to perform the least squares fit to the one-dimensional vector of measured data. If the input data vector has length N.sub.D and the number of variables is N.sub.V, then a N.sub.D by N.sub.V matrix multiplication must be performed for each laser pulse. This is well within the capabilities of a microcomputer, since the pseudo-inverse matrix used in the multiplication is precalculated once and stored in the bottom detector computer 32. The digital delay generator 16 is then set to the least squares fitted value of .notident..sub.B, which is the total round trip delay time over the slant path from the laser pulse emission to the bottom return.

DEPR:
Another feature of this invention relates to the elimination of the discriminator 106. The drawback of discriminator 106 (which acts as a comparator) is that if the water is too deep, the glint off the water surface (at .tau..sub.s in FIG. 4) may overwhelm or confuse and thereby mask the return reflection from the bottom (at .tau..sub.B in FIG. 4) resulting in a false reading (e.g., the bottom detector will measure the distance to the water surface rather than bottom). In contrast, using the digital converter 30, computer 32 and the algorithms described above, the present invention will accurately distinguish between water surface glint and bottom reflection. In fact, the bottom detector 14 of this invention will produce the output curve of FIG. 4 together with all of the information set forth in FIG. 4 for each laser pulse. Thus, not only does the present invention provide an accurate measurement of the bottom, but additionally it provides accurate information on air visibility, water depth, water clarity, wave height, bottom roughness and bottom reflectance.

CLPR:
1. An apparatus for detecting and imaging from an airborne platform an object at least partially enveloped by water, the water having a surface and a bottom, comprising:

CLPV:
converting means for converting said detected pulses of light to a video image of said object; and